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Phosphorus loss and speciation in overland flow from a plantation horticulture catchment and in an adjoining waterway in coastal Queensland, Australia

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Abstract. Phosphorus (P) in overland flow from horticulture farms in coastal Queensland, Australia, could eutrophy coastal freshwater and marine habitats environments nearby. The potential for such eutrophication was investigated in a coastal macadamia plantation under commercial production. During the 13-month study, P losses in overland flow were quantified in a 0.24-ha farm catchment with a 3.1% gradient, during five consecutive storm events. These events were within expected short- and long-term episodic rainfall frequencies and intensities. Runoff occurred when such storms generated between 20–40 mm/h of rainfall for >9 min. Calculated annual losses of total P were 0.32 kg/ha.year, comprising dissolved inorganic P (DIP, 0.28 kg/ha.year), particulate P (0.03 kg/ha.year), and dissolved organic P (0.01 kg/ha.year). DIP represented 88% of all losses and this was attributed to excessive fertilisation and untimely applications. Losses of total P were generally higher than those reported in comparable studies.

Concentrations of DIP in runoff were 20–200-fold higher than those found in other coastal catchments in Queensland. High concentrations of DIP were present in the topsoil of the non-fertilised, inter-row areas of the farm catchment and this was attributed to transfer and deposition of DIP from adjacent fertilised tree beds during storm flow. Therefore, it can be expected that farm runoff will be enriched with DIP from these areas for an indeterminate period despite any future remediation to fertiliser management. The weighted average of DIP in farm runoff was 2.01 mg/L, whereas it was 0.005 mg/L in a catchment stream bordering the farm, showing a steep concentration gradient between the two ecosystem compartments. Together with nitrogen (N) losses in runoff, reported previously, an N : P molar ratio of 2 : 1 was contained in the farm runoff. This was well below the growth-limiting threshold for aquatic organisms, as determined by the Redfield ratio of 16 : 1 (N : P). The entry of nutrient-enriched farm runoff, as detailed in this study, into the catchment stream and the proximity of such waterways (8 km) to the coastline may also have implications for the near-shore (oligotrophic) marine environment during periods of storm flow. Altogether, this work revealed the high risk of eutrophication from farming landscapes such as the one under study.

Additional keywords: eutrophication, macadamia, runoff, ortho-phosphate.

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Introduction

The eutrophication of freshwater and marine environments by phosphorus (P) has been extensively documented for major aquatic ecosystems such as the Chesapeake Bay, USA (Boesch *et al*. 2001), the Lake Okeechobee watershed, USA (Flaig and Reddy 1995), the Gulf of Mexico (Alexander *et al*. 2008), and the Peel-Harvey Estuary and the Great Barrier Reef region of Australia (Hodgkin and Hamilton 1993; Fabricius 2005; Fabricius *et al*. 2005). These studies also describe the consequent harm by eutrophication upon environmental stock from toxic algal blooms, seasonal hypoxia, diminished sea and estuarine grass beds, and the decalcification of near-shore coral reefs.

These studies and others cite the proximity of farming activities to waterways as the greatest single influence leading to the impairment of these waterways from eutrophication (Carpenter *et al.* 1998). In the south-eastern and northern coastal region of Queensland, Australia, coastal farming catchments border the Great Barrier Reef World Heritage Area (GBRWHA), the world's largest expanse of protected marine habitat, which is sustained by an oligotrophic marine environment. Modelled calculations have estimated that 4.7–10.3 kt P/year of anthropogenic P contained in overland flow is discharged into the GBRWHA from these coastal farming catchments (McKergow *et al*. 2005). An increasing concern about threats to water quality in the GBRWHA from eutrophication led to the implementation of a nutrient management zone (NMZ) (Anon. 2007). Horticulture farming in the NMZ was assessed as an activity with high risk of nutrient loss into the GBRWHA (Anon. 2007).

Despite the threat of eutrophication in the GBRWHA and elsewhere, limited information is available on surface losses of P from horticulture farms in the NMZ or in similar agroecosystems worldwide. To estimate the potential magnitude of P losses from horticulture in the NMZ, we undertook field investigations in a plantation horticulture farm. This production system was chosen for several reasons. First, such farms use a raised-bed system of production, and second, farms are often on sloping landscapes that are bordered by coastal streams and rivers within 50 km of the NMZ. A macadamia farm was chosen as a representative model of such farming activity, and this paper reports our findings on P runoff from the farm and in water and sediment of an adjoining catchment waterway.

Materials and methods

Location of study

The field study was carried out in the coastal Burnett catchment of South East Queensland, ~24.866°S and 152.349°E. The area has a subtropical climate. Average maximum temperatures for the regional centre of Bundaberg vary from 22 to 30°C and long-term average rainfall is 1002 mm (SILO 2005).

Farm study

Nutrient runoff and surface soil concentrations of P were measured in a commercial macadamia plantation between October 2005 and July 2006. The farm soil is classified locally as a Kandosol by the Australian Soil Classification or as a Red Earth according to the Great Soil Group (Anon. 2004). The 0–10 cm soil layer was classified as loamy sand with an alkaline pH (Stork *et al.* 2009). Macadamia trees flowered between July and September and their nut formation occurred between October and February. Mechanical harvesting spanned March–July with the peak harvests in May and June. Macadamia trees were at 3.9 m by 3.9 m spacings in bare-soil raised beds which were ~28 cm high at their crest (Fig. 1). A 3.4-m, grassed, inter-row area separated adjacent beds (Fig. 1). This configuration gave a planting density of 351 trees/ha. Trees were irrigated with micro-jet sprinklers spaced equidistantly between trees and 30 cm above bed surfaces. A granular form of triple superphosphate fertiliser (0.0% N, 20.7% P, 15% Ca, 1% S) was mechanically broadcast onto these beds on 13 July 2006.

Measurement of surface runoff at the study farm

In mid-September 2005, a 0.24-ha catchment (165 by 15 m) with a gradient of 3.1%, made up of three rows of 8-year-old macadamia trees with two inter-rows, was established on the farm to measure and sample surface runoff (Fig. 1). Surface flow from the catchment was directed into a San Dimas flume by grassed, V-shaped embankments ~15 m in length and 20 cm high (Fig. 1). The embankments were constructed from soil in a shelter belt undisturbed by agricultural activity in close proximity to the catchment. The flume had a throat height/width of 50/20 cm and a length of 140 cm. It was connected to automated flow-sensing equipment, a water sampler, and a tipping bucket rain gauge (Isco 674, Teledyne Isco, Lincoln, NE). This equipment was integrated to coordinate measurements of flow through the flume (L/s) and rainfall intensity (mm/min), and to sample and store the flow in glass containers. The latter was at preset time intervals activated during events where flow exceeded a height of 5 mm in the throat of the flume, equivalent to an overland surface flow rate of 0.7 mm/h. Samples were retrieved within 12 h of a flow event and were maintained at 4°C in glass bottles under ice until dispatch for analysis. Data from five runoff events were collected between October 2005 and July 2006.

Measurement of soil phosphorus

Soil samples were extracted to a depth of 5 cm using a 6-cm-diameter Riverside hand auger (Eijkelkamp, Giesbeek, The Netherlands). Temporal changes to soil orthophosphate were measured within each of three replicate raised beds of the 0.24-ha catchment (Fig. 1). Samples were removed at two equidistant sampling points between the crest and the edge of the beds and repeated at 16-m intervals along the length of 165 m of each tree-row, alternating between the left and right of the row (Fig. 1). The 20 cores derived from each of the rows were bulked individually as a replicate measurement and stored in a clean plastic container. Sampling was undertaken at approximate monthly intervals between October 2005 and July 2006 and at least 2 m from a previous sampling.

Spatial sampling was conducted after the fourth runoff event in July 2006. Samples were extracted along a length of ~175 m of each of the two inter-rows, at ~10-m intervals, from the crest of the catchment to the edge of the tree-line. The latter was within ~15 m of the bordering catchment stream. At each interval, samples were removed from three equidistant points spaced across each 3.4-m, grassed, inter-row area and the distance of each sampling interval from the tree-line was recorded. The three samples from each interval were bulked into individual, clean plastic containers. Both inter-row areas sampled in this way provided two replicated measurements for each of the 17 sampling intervals along the catchment gradient.

All soil samples were placed in a forced-fan dehydrator and air-dried to constant weight at 40°C within 2 h of a sampling. Samples were then ground to pass through a 2-mm sieve before nutrient analyses.

Stream sediment and water sampling

Sediment and water samples were collected under quiescent conditions along a length of ~5 km of stream bordering the study catchment (Fig. 1). The study catchment was located at the approximate midpoint of this 5-km sampling length. This stream drained a catchment of ~7000 ha of mixed farmland ~8 km from a coastline that was within the NMZ. The average width of the stream over this distance was ~6 m and the depth of sediment sampled was up to ~50 cm. The sediment had the properties of an acid sandy loam, according to key physical and chemical analyses cited in Stork *et al*. (2009).

Stream sampling was undertaken in August 2006 at 10 different sampling locations spaced over the 5-km length. At

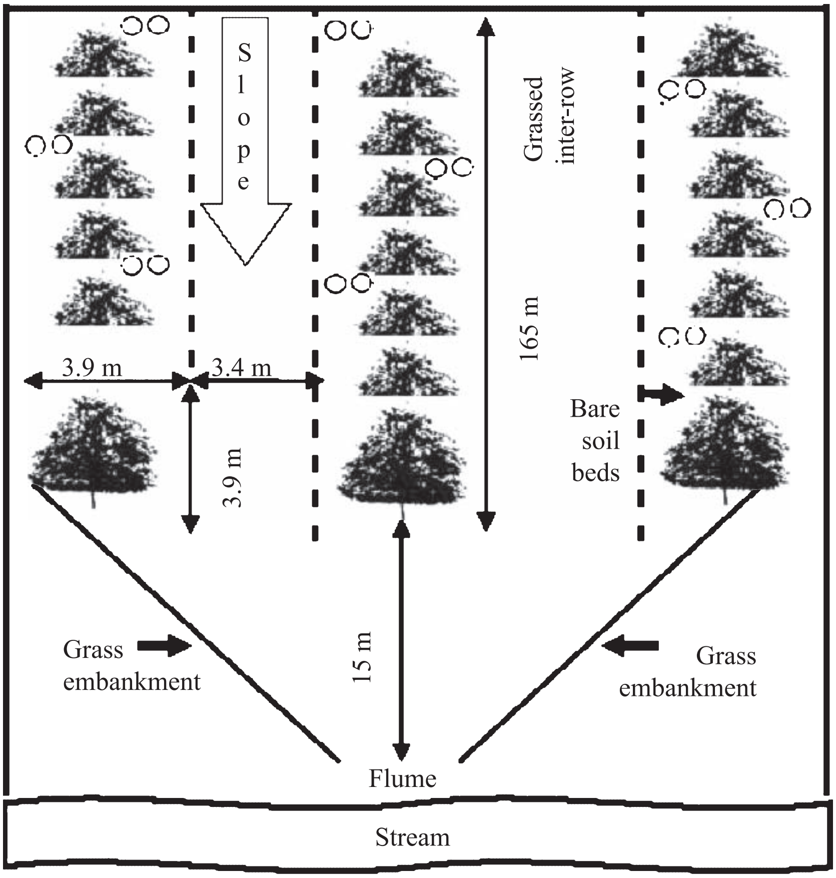

Fig. 1. Depiction of the 0.24-ha macadamia catchment used in the study (not to scale), showing the planting configuration of trees within bare soil beds, the adjacent grassed inter-rows, and the runoff collection flume positioned at the edge of the farm and alongside the catchment stream. Soil sampling points within the raised beds are depicted by circles (O O). Sampling points in the grassed inter-row are not-displayed.

each location, a 5-cm-diameter piston sampler (Enviroequip, Port Melbourne, Vic.) was used to retrieve undisturbed sediment from five points within a 4-m^2 area of stream. The samples from each location were individually bulked in glass jars. A collection rod fitted with a 1-L bottle was used to collect water samples from a 10-m swathe at each sampling point. All samples were immediately stored under ice and transferred to a refrigerator ~2 h later and kept at 4°C until analysis.

Nutrient analyses

Bio-available P, as orthophosphate, in the farm soil samples was determined by method 9B2 detailed in Rayment and Lyons (2011), which incorporates the extraction method of Colwell (1965) and colourimetric quantification according to Murphy and Riley (1962). In summary, the orthophosphate in samples was extracted, after shaking for 16 h, in a 1 : 100 soil : solution of 0.5 M sodium bicarbonate buffered at pH 8.5, and the filtered extract was quantified for orthophosphate by automated colourimetry.

Total P in unfiltered water samples (TKP) and total dissolved P (DKP) in 45-µm filtered samples was extracted by Kjeldahl (block) digestion according to the method of Bremner and Mulvaney (1982). Quantification of P in the extractant was determined colourimetrically by the method of Murphy and Riley (1962). Dissolved orthophosphate in water samples (PO_4-P) was quantified, without extracting solvents, by the method of Murphy and Riley (1962).

Total P in stream sediments was extracted by the tri-acid (nitric acid, perchloric acid, and hydrogen peroxide) microwave digestion method of Milestone (1995), and the extractant quantified by inductively coupled plasma-optical emission spectrometry (ICP-OES).

Total suspended sediment (TSS) in waters was quantified from a measured volume of a homogeneous runoff sample. The runoff was filtered through a weighed, 45-µm glass-fibre filter disc that had been rinsed and oven-dried (105°C) before filtration. The filter disc with the filtered residue was oven-dried and weighed again. The difference in weights of the filter disc gave the total suspended sediment content of the measured volume of sample.

Data analyses

Concentrations of P in runoff waters were converted to amounts exported per unit area (g/ha) according to corresponding flow volumes (m^3/ha). The composition of P fractions in runoff was quantified according to the following calculations: (*i*) total P (TP) = TKP; (*ii*) particulate P (PP) = TKP – DKP; (*iii*) total dissolved P (TDP) = DKP; (*iv*) dissolved organic P (DOP) = DKP – PO_4-P; (*v*) dissolved inorganic P (DIP) = PO_4-P; (*vi*) total sediment P (TSP) = PP/TSS.

The weighted averages of DIP and DOP in mg/L and TSP (%) were calculated from total losses of each fraction divided by total flow at each runoff event for comparison with like fractions in stream sediment and water samples.

Results

Temporal variation in soil phosphate within tree beds at the study farm

At the first soil sampling, on 21 October 2005, the concentration of orthophosphate was 136 (±8) mg/kg soil within the raised beds (Fig. 2*a*). From this sampling time, orthophosphate concentrations gradually declined to a lower range of 109 (±6) and 115 (±8) mg/kg soil between the seventh and the tenth sampling, on 22 March and 22 June 2010, respectively (Fig. 2*a*). Following a fertiliser application of 62 kg P/ha on 13 July 2010, soil concentrations rose steeply to 144 (±2) mg/kg soil, as revealed by the last sampling on 21 July 2010 (Fig. 2*a*). The corresponding field rates of orthophosphate at these sampling times were equivalent to 63 (±4), 50 (±2), 53 (±4), and 67 (±2) kg P/ha, respectively, within the 0–5 cm soil layer.

Rainfall, irrigation and surface flows at the study farm

Runoff events occurred between 21 October 2005 and 28 July 2006 (Fig. 2*b*). In this period, total rainfall and irrigation amounted to 709 and 458 mm, respectively. During the storm season, between October 2005 and March 2006, the majority of rainfall events were either ≤10 mm or ≤20 mm episodes (Fig. 2*b*), and accounted for 76% and 93% of all events, respectively. Irrigation, applied at 26 mm per event, was most frequent in this period, when the formation and maturation of macadamia nuts was occurring (Fig. 2*b*). Rainfall and irrigation during the storm season totalled 446 and 305 mm, respectively. There were no runoff events between August 2006 and the end of monitoring period, in January 2007, during which time drought conditions prevailed (data not displayed).

Total rainfall during runoff events on 21 October (RO1) and 15 November (RO2) 2005, and 18 April (RO3), 10 June (RO4), and 28 July (RO5) 2006 amounted to 23, 19, 31, 126, and 53 mm, respectively, (Fig. 2*b*). These events were interspersed with episodes totaling 40, 30, 36, 20, 20, and 21 mm that did not produce runoff (Fig. 2*b*). There were several occasions when irrigation closely followed rainfall episodes, and a

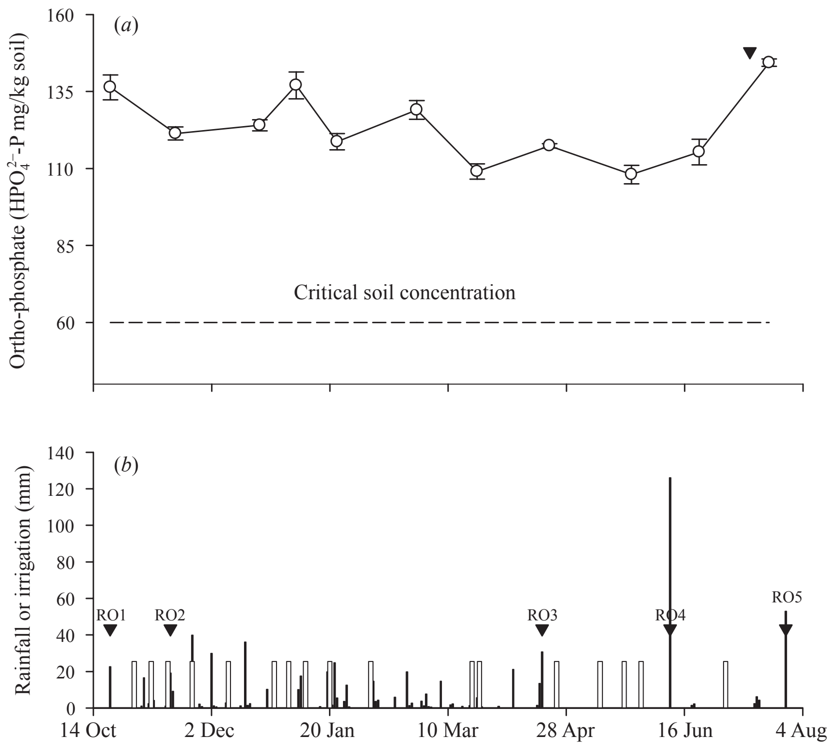

Fig. 2. (*a*) Temporal soil concentrations (–O–, error bars denote the standard error of means) of orthophosphate within 0–5 cm of macadamia beds during 2005–06; ▼ denotes fertiliser application of 62 kg P/ha on 13 July 2006. (*b*) Corresponding total rainfall (▮) and irrigation (▯), and runoff events (▼) at the study farm: RO1, 21 October 2005; RO2, 15 November 2005; RO3, 18 April 2006; RO4, 10 June 2006; RO5, 28 July 2006. [Part (*b*) reproduced from Stork *et al.* 2009 for clarity of interpretation of results.]

single runoff event (RO2) eventuated under these conditions (Fig. 2*b*).

Rainfall intensities were recorded in minute intervals for all storm events during the monitoring period, except for RO4 when intensities in 30-min intervals from an auxiliary weather station at the site were matched to RO4 flow data (Fig. 3*d*) following a malfunction in the primary rain gauge.

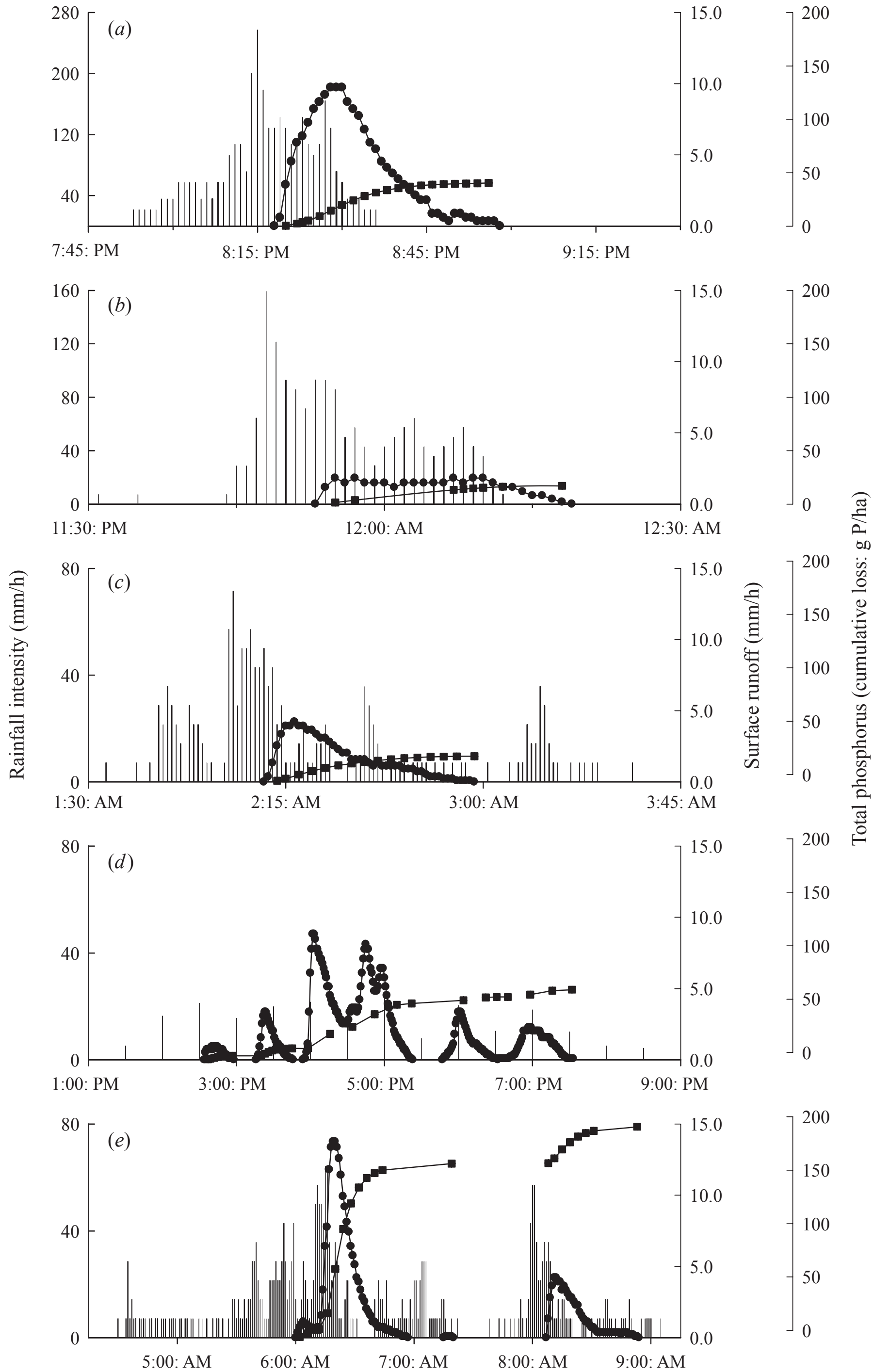

Fig. 3. Rainfall intensity (|), surface runoff (●), and cumulative loss of total phosphorus (■) during storm events at the study farm on: (*a*) 21 October 2005 (RO1), (*b*) 15 November 2005 (RO2), (*c*) 18 April 2006 (RO3), (*d*) 10 June 2006 (RO4), and (*e*) 28 July 2006 (RO5). [Rainfall intensity and surface runoff reproduced from Stork *et al.* 2009 for clarity.]

The duration of rainfall events at RO1, RO2, RO3, and RO5 was between 0.5 and 8.3 h, and intensities peaked between 257 and 64 mm/h but were rarely maintained for >2–3 min (Fig. 3). Average peak intensities over a 5-min period in these events ranged from 180 mm/h in RO1 to 110 mm/h in RO2 and 50–55 mm/h in RO4 and RO5. Intensity–frequency–duration (IFD) analyses for the location predicted that intensities of RO1 would occur every 5 years, while RO2, RO3, and RO5 would occur annually, or at greater frequency (Stork *et al.* 2009). IFD analyses also predicted that the average rainfall intensity over the entire duration of rainfall at RO1, RO2, RO3, and RO5 was expected to occur annually, while RO4 would occur every 10 years (Stork *et al.* 2009).

Surface flows occurred when rainfall intensity exceeded 40 mm/h for RO1, RO2, and RO3 and 20 mm/h for RO5 at durations >9 min (Fig. 3). These trigger events were also predicted to occur annually or at a greater frequency by IFD analyses (Stork *et al.* 2009). The total volume of surface flow during RO1, RO2, RO3, RO4, and RO5 amounted to 26, 6, 13, 87, and 45 m^3/ha, respectively. These flow volumes were strongly related to the total rainfall during these runoff events ($R^2 = 0.89$), and accounted for $5.3 \pm 1.1\%$ of the total episodic rainfall (Stork *et al.* 2009).

Phosphorus losses in surface flows at the study farm

The duration of surface flow during RO1, RO2, RO3, RO4, and RO5 was 0.6, 0.4, 0.8, 4.1, and 2.6 h, respectively (Fig. 3*a–e*). The cumulative losses of TP for these durations amounted to 40, 17, 24, 66, and 197 g P/ha, respectively (Fig. 3*a–e*). In the first quarter of all runoff events, the cumulative loss of TP varied widely, between 15% and 75%, but after the first half of each runoff event, ~75% TP had been lost (Fig. 4).

The components of TP in runoff were DIP, PP, and DOP (Fig. 5*a–c*). Generally, there was little difference between the mean and median concentrations of each fraction at each event, indicating that their average concentration would be a sound benchmark. Mean concentrations of DIP ranged between ~1 and 4 mg P/L, while PP and DOP were at 10–100-fold lower concentrations, with ranges 0.01–0.4 mg P/L and 0.01–0.2 mg P/L, respectively, (Fig. 5*a–c*). There was no consistent numerical relationship between DIP, PP, or DOP across all events (data not displayed).

The total loadings of all fractions in runoff amounted to 345 g P/ha (Table 1). DIP accounted for 303 g P/ha, while PP and DOP accounted for 36 and 6 g P/ha, respectively (Table 1). Total sediment losses for all events amounted to 10.5 kg/ha. There were no consistent proportional relationships between PP, DOP, and DIP across all events,

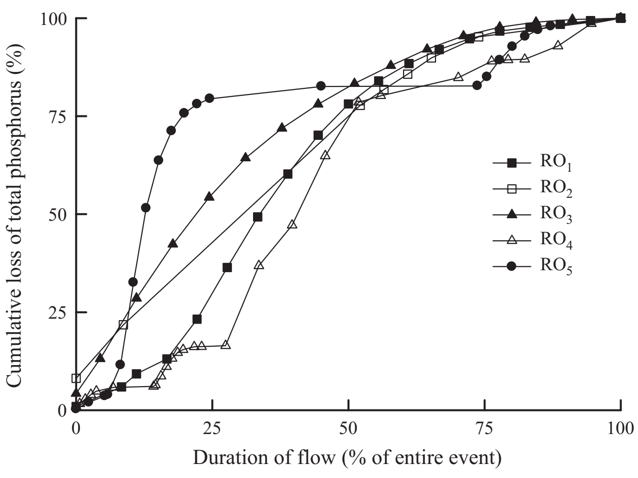

Fig. 4. Cumulative loss of total phosphorus over the duration of a runoff event.

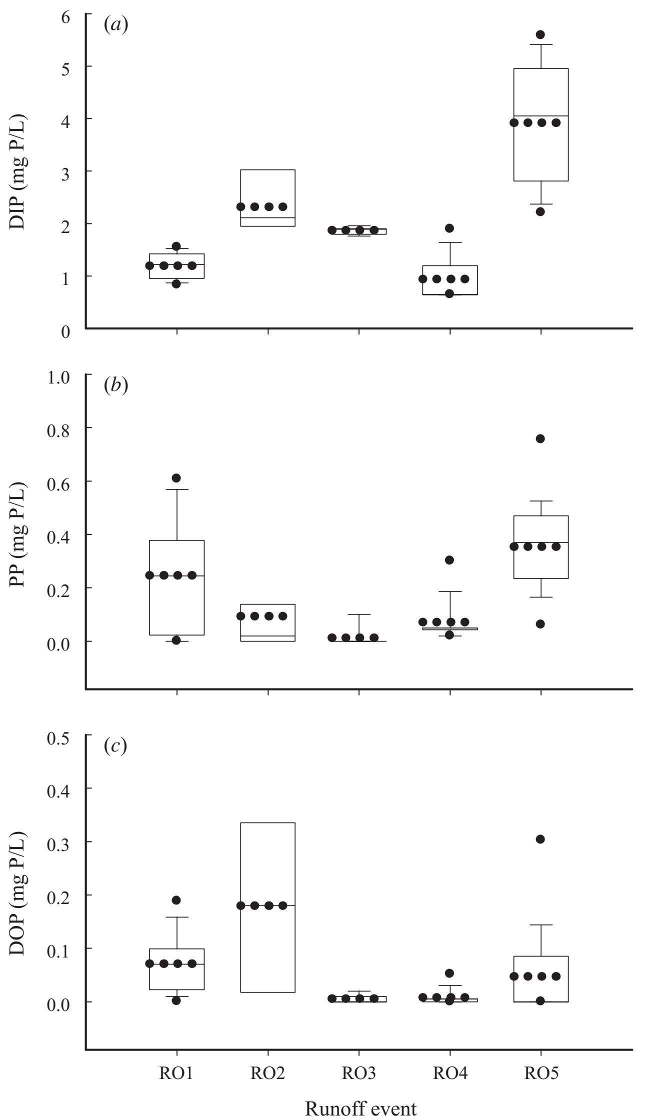

Fig. 5. Summary of concentrations of (*a*) dissolved inorganic phosphorus (DIP), (*b*) particulate P (PP), and (*c*) dissolved organic P (DOP) during runoff events, using box-plot statistics. Lines of dots (•••) and lines (—) within boxes represent mean and median values, respectively. The 5th and 95th percentiles are represented by single dots (•); the 25th and 75th percentiles by box boundaries; and the 10th and 90th percentiles by 'whiskers' (⊥). Values of missing symbols are identical to the next closest statistic.

Table 1. Composition of total phosphorus (P) loadings (g/ha) in runoff at the study farm

PP, Particulate P; DOP, dissolved organic P; DIP, dissolved inorganic P. Total P for all events = PP + DOP + DIP = 345 g/ha

Runoff event	PP	DOP	DIP
RO1, 21 October 2005	10	2	28
RO2, 15 November 2005	0	1	15
RO3, 18 April 2006	0	0	24
RO4, 10 June 2006	5	0	61
RO5, 28 July 2006	20	3	175
Total	36	6	303

nor were there consistent trends between the loadings of DIP in runoff events and temporal soil orthophosphate concentrations (Table 1, Fig. 2). The highest loading of all P fractions was a large, disproportionate loss of DIP at RO5 (Table 1). It represented 58% of total DIP losses and occurred 15 days after the sole fertiliser application, of 62 kg P/ha, during the monitoring period. The aggregate loss of DIP and total surface flow volume in runoff events, excluding data for RO5, formed an exponential relationship, suggesting that loadings of DIP into runoff became limiting as total flow volumes increased from soil that was not recently fertilised (Fig. 6). A functional relationship for either PP or DOP was not evident for the runoff events (data not displayed).

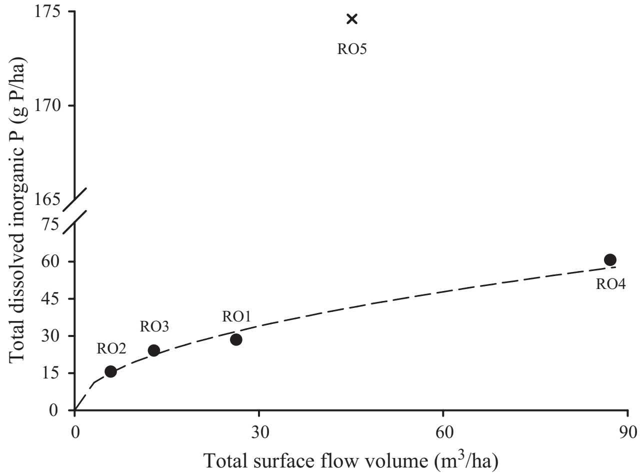

Fig. 6. Relationship between total dissolved inorganic phosphorus (●, DIP) loadings in runoff at runoff events RO1, RO2, RO3, and RO4 at the study farm and the corresponding total volume of surface flows (TSF). The functional relationship of the fitted curve was $DIP = 6.301 \times TSF^{0.495}$; $R^2 = 0.98$. The dates of runoff events RO1–RO5, respectively, are 21 October 2005, 15 November 2005, 18 April 2006, 10 June 2006, 28 July 2006. Excluded data point at RO5 denoted by X, where fertilisation occurred 15 days before the event.

Spatial variation in concentrations of soil phosphate within inter-rows at the study farm

Surface (0–5 cm) soil concentrations of orthophosphate along the sampling gradient in the inter-row area of the runoff block, from the crest of the runoff block to the edge of the catchment stream bordering the farm, are displayed in Fig. 7. Orthophosphate concentrations at the bottom of the slope, covering a distance of ~40 m to the adjacent waterway, were distinctly lower, at 125 (±1) mg/kg soil, compared with concentrations averaging 155 (±5) mg/kg soil to the crest of the gradient (Fig. 7). These concentrations were equivalent to 38 (±0.4) and 47 (±2) kg P/ha, respectively. The average orthophosphate concentration, from 40 m to the crest, was 31 mg/kg soil higher than the average concentration of 124 (±4) mg/kg soil within the raised beds (Fig. 2*a*) for the entire period of soil sampling. Fertiliser was not applied in the inter-row area.

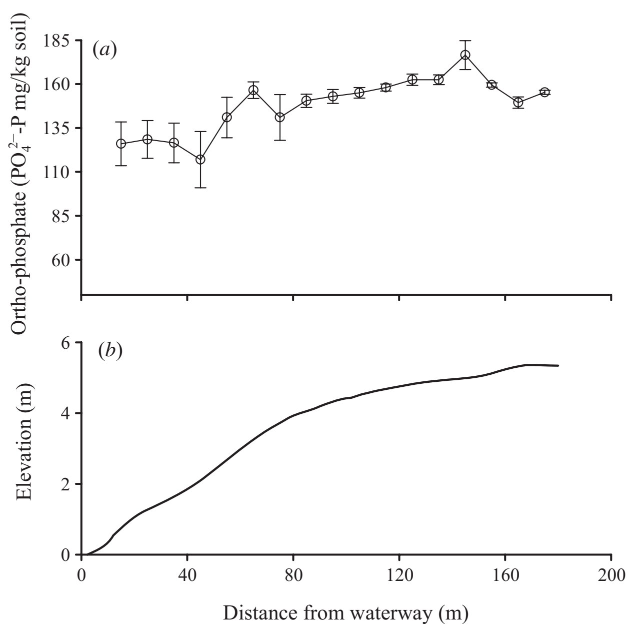

Fig. 7. (*a*) Spatial soil concentrations of orthophosphate (–O–, error bars denote the standard error of means) within 0–5 cm of the inter-row area of the study farm; (*b*) the topography of the plantation inter-rows. Data were collected 24 July 2007 following RO1, RO2, RO3, and RO4. [Part (*b*) reproduced from Stork *et al.* 2009 for clarity.]

Phosphorus in water and sediments in the catchment stream and in farm runoff

The weighted average concentrations of DOP and DIP and the percentage of TSP from runoff events were compared with DOP, DIP, and TSP in the catchment stream shortly after the period of monitoring farm runoff (Table 2). The concentration of DOP in stream water was slightly higher than in farm runoff (Table 2). However, TSP and DIP fractions in farm runoff were ~10-fold and 400-fold higher, respectively, compared with stream concentrations (Table 2). Consequently, the DIP : DOP ratio in the stream water was 0.06, whereas it was ~34 for farm runoff.

Discussion

Temporal variation in soil phosphate within tree beds at the study farm

During an 8-month period between nut formation in October 2005 and peak harvest in June 2006, surface soil concentrations

Table 2. Average concentrations (± s.e.) of dissolved and sediment phosphorus (P) fractions in runoff from the study farm and in the adjoining catchment stream

DOP, Dissolved organic P; DIP, dissolved inorganic P; TSP, total sediment P

	Farm runoff	Stream
DOP (mg/L)	0.06 ± 0.04	0.08 ± 0.01
DIP (mg/L)	2.01 ± 0.57	0.005 ± 0.002
TSP (%)	0.27 ± 0.06	0.028 ± 0.004

of orthophosphate in the runoff block had a cyclical range between 109 and 144 mg/kg soil. The latter concentration arose from a fertiliser application broadcast immediately after peak harvest, as part of the preparatory regime for the next production cycle. This raised soil concentrations to the highest levels during the 10-month monitoring period. The critical soil concentration of orthophosphate in surface soil required for the optimum yield of mature macadamia plantations in this soil type is 60 mg/kg soil (Moody and Bolland 2001). Similar work in the region determined the critical orthophosphate concentration range between 84 and 88 mg/kg soil for mature macadamia plantations in other soils (Stephenson *et al*. 2002). These benchmarks therefore imply that surface orthophosphate soil concentrations at the study site were ~1.5–2.25-fold higher than requirements for the optimum yield of macadamia. Soil surveys have found that excessive surface concentrations of orthophosphate are not uncommon in contemporary tree-cropping enterprises in coastal Queensland, as evidenced by a majority of the survey sites which had topsoil phosphate concentrations >60 mg/kg (Rayment and Bloesch 2006).

Rainfall, irrigation, and surface flows at the study farm

Total rainfall during all runoff events was equivalent to 36% of the total rainfall during the monitoring period. Many storm events did not generate runoff at amounts of episodic rainfall greater than those of the five runoff events during similar seasonal conditions. In several instances, irrigations closely preceded such events but surface flow eventuated in only one such event (RO2). Altogether, this showed that total amounts of episodic rainfall alone, or in combination with recent irrigation, could not predict runoff events. Rainfall episodes that caused surface flows were characterised by intensities and durations that were 20–40 mm/h for >9 min. These intensities and durations were representative of events that occur either annually or in the longer term according to IFD analyses. Comparison of runoff-initiating rainfall intensities and durations with another field study in the region indicated that catchment gradients moderate the commencement of surface flow. Overland flows were initiated at rainfall intensities >20 mm/h when durations exceeded 26 min on a Podosol with a similar surface texture but a lower site gradient of 1.4% (Stork *et al*. 2008). Considerably shorter durations before runoff in the present study were likely to have been due to the steeper gradient, of 3.1%, on the Kandosol.

Higher internal drainage in the Kandosol was also evident when compared with results for the Podosol. Total surface flow volumes were ~6% of the total precipitation during runoff events on the Kandosol whereas it amounted to 10.7% on the Podosol (Stork *et al.* 2008). These differences could be attributed to differences in internal drainage and are corroborated in a more specific study of *in-situ* saturated hydraulic conductivities of Kandosols, which were 6-fold greater than of a Podosol in the study region (Verburg *et al*. 2001). The rate of internal drainage in Kandosols implies high leaching potential for phosphate in the study soil, especially during runoff events where net drainage into soil, after accounting for overland flow, amounted to ~237 mm. Significant leaching losses of phosphate occurred under considerably lower amounts of internal drainage in a Vertosol under irrigated horticultural production (Stork *et al*. 2003). Quantification of leaching losses of P in the present study was not within the scope of this paper.

Phosphorus losses in surface flows at the study farm

Loadings of TP into overland flow were rapid, and cumulative losses of 75% of TP occurred in the first half of the duration of each runoff event. The lack of any numerical relationship between concentrations of DIP, PP, or DOP during overland flow indicated that the loadings in runoff of each of these species were separate and independent species of P. Thus, the elution of one fraction was not related by quantity or concentration to another.

Compared with RO4, loadings of DIP at RO5 were 3-fold higher with approximately half the volume of overland flow, suggesting that there was substantial mass flow of DIP at RO5. This indicated that phosphate in the fertiliser application of 62 kg P/ha 15 days before RO5 had not adsorbed to completion in topsoil, unlike RO1, RO2, RO3, and RO4, which were not preceded by recent fertilisation. The large loss (~58% of total DIP losses) at RO5 concurred with other studies where up to 57% of total DIP runoff losses occurred within 21 days of superphosphate application (McDowell *et al*. 2010). Numerous other studies have also showed that the largest annual losses of DIP from various farming systems occurred with recently applied superphosphate (Hart *et al*. 2004). Altogether, this highlighted the critical need for optimal timing of applications of soluble fertiliser phosphate to minimise loss in overland flow by basic and disciplined farm management strategies.

When losses at RO5 was excluded from the relationship between DIP and surface flow, an exponential function was derived which predicted that loadings of DIP would reach their equilibrium point when surface flow volumes approached 90 m^3/ha. This functional relationship was similar to P release kinetics demonstrated in other studies (McDowell and Sharpley 2003). This confirmed that the release of DIP in surface flow was governed by soil sorption, where aged residues of fertiliser phosphate are the dominant fraction in surface soil.

The TP losses between October 2005 and July 2006 amounted to 0.35 kg/ha and the annual loss, adjusted for period between September 2005 and October 2006, was 0.32 kg/ha.year. This represented ~0.6% of the average surface soil load of orthophosphate. Comparison of this annual rate of loss with other work is difficult, as findings from fertilised agriculture activities under natural conditions of rainfall, irrigation, soil type, and slope are rare, particularly for horticultural production. The few comparisons that are available show that annual losses of TP from the present study are at the higher end of reported losses. Annual losses of total P in well-fertilised, hilly, clay loam pastures in Taita, New Zealand, were 0.29 kg/ha.year (McColl *et al*. 1977). Conversely, in a silty clay loam sugarcane catchment with slopes of 5–12% and where the P fertiliser regime was similar to those in macadamia, annual losses of total P were ~0.04 kg/ha (Ng Kee Kwong *et al*. 2002). If the annual loading reported in our study occurs at the catchment scale from the surrounding 7000-ha mixed farming landscape, it would entail a significant annual loading of P into the study stream, particularly DIP, which accounted for ~88% of total loadings into the waterway.

The dominance of DIP in runoff was in contrast to many studies where PP is the major fraction (Hart *et al*. 2004). The concentration of PP in runoff has been found to have direct relationship to the extent of soil disturbance by cultivation practices (Puustinen *et al.* 2005). In our study, the considerably lower loadings of PP compared with DIP were possibly due to low sediment losses, which were minute when compared with runoff in cultivated farming systems in which PP was the dominant species (Ng Kee Kwong *et al*. 2002; Rohde and Bush 2011; Rohde *et al*. 2011). The high loadings of DIP emanated from excessively high surface soil concentrations of phosphate. As previously discussed, they were well in excess of known critical soil concentrations for macadamia, and such high levels of phosphate are not uncommon in horticulture farms of coastal Queensland, indicating that present fertiliser regimes are a critical factor governing the extent of surface losses of phosphate in this region.

Spatial variation in concentrations of soil phosphate within inter-rows at the study farm

Concentrations of surface soil orthophosphate in the inter-row area were higher by ~20 mg/kg soil from the crest of the runoff block to within 40 m of the catchment stream, indicating a build-up of phosphate in this unfertilised inter-row from tree beds during runoff events. The lack of a similar high deposition within the 40-m stretch of inter-row terminating at the stream suggested deposits here were eroded by the steepness of its gradient. Therefore, these results suggested that phosphate nutrient loads can accumulate in non-target areas in a farming landscape as a consequence of periodic runoff events. Prudent fertiliser management within the target (tree-bed) areas could remedy the practice of excessive fertiliser application. However, such measures are unlikely to have an immediate effect on diminishing loadings of phosphate into catchment waterways until the build-up of phosphate in non-target (inter-row) areas is dissipated. Therefore, the aims of future fertiliser management should include abatement strategies for the non-target areas of such farming systems. A grass catch-cropping system which is designed to be most active during the storm season is one possibility. Other studies have found nutrient sequestration by catch-cropping is a feasible method to minimise off-site losses of nutrients in stone- and pome-fruit orchards (Stork and Jerie 2003).

Phosphorus in water and sediments in the catchment stream and in farm runoff

The average weighted concentrations of DOP and TSP in farm runoff and the stream were very similar. The average DIP concentration of the stream, 0.005 mg/L, was well below the defined threshold of 0.015 mg/L determined for slightly to moderately disturbed lowland streams for the region (Anon. 2009). The considerably lower DIP level in the catchment stream may have arisen due to seasonal sequestration into sediments or the embankments of the stream or riparian filtration. Alternatively, it may indicate that this stream was relatively pristine, with its average DIP at the threshold of 0.005 mg/L determined for freshwater lakes and reservoirs of the region (Anon. 2009). The average weighted concentration of DIP (2.01 mg/L) in farm runoff was ~400-fold higher than in the stream. This suggested there was a steep concentration gradient of bio-available P between farming landscapes and the adjoining waterway. This concentration gradient was extraordinarily high when compared with known benchmarks of DIP loss. Compilation by McKergow *et al*. (2005) of numerous runoff studies from various land uses in the GBRWHA showed that weighted averages of DIP from runoff from pristine rainforest, general horticulture, and banana production were 0.010, 0.030, and 0.100 mg/L, respectively. The weighted average of DIP in our study was 20–200-fold higher, showing that extremely high levels of phosphate loss can occur from farming regimes such as the one under study and may be a potential long-term source of eutrophication in streams nearby.

Numerous studies have concluded that phosphate is a key factor for the eutrophication potential of both freshwater and marine environments (see *Introduction*). Total nitrogen (N) losses from this study amounted to 283 g N/ha (Stork *et al.* 2009), while losses of TP were 345 g P/ha. This represented a molar N : P ratio of 2 : 1 and was well below the Redfield ratio of 16 : 1(N : P), which is held as the growth-limiting threshold for aquatic organisms such as phytoplankton (Mitchell *et al.* 2005). The combined N and P quantified in our studies shows that an extremely rich N : P source in runoff was available for the stimulation of aquatic growth.

The indicative threshold values for P stress upon slightly disturbed aquatic ecosystems have been reported to be 0.01 mg TP/L for tropical regions of Queensland, Australia (Mitchell *et al*. 2005). The in-stream concentration of TP approximated this benchmark, showing it was already near to a point of recognised perturbation which would be exacerbated by P loadings from runoff as quantified in our study.

Conclusion

The largest P loadings in runoff were orthophosphate, and this strongly implicated highly water-soluble fertiliser, such as superphosphate, as its source. An excessive fertiliser regime of superphosphate, by both applied rate and timing, was influential in a significant loss of orthophosphate in runoff. Losses were higher than those reported in comparable studies. Orthophosphate is the most bio-available form of P, and therefore, its potential to eutrophy coastal waterways is likely to be high by entry of runoff from farming regimes similar to those of our study. This also presents a possible risk of nutrient loading to near-shore areas of the GBRWHA during storm flows, given the waterway's proximity (8 km) to the coastline. The functional relationship between DIP and total surface flow volumes provides a simple method for estimation of loadings of orthophosphate from farming landscapes into adjacent waterways.

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References

Alexander RB, Smith RA, Schwarz GE (2008) Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River basin. *Environmental Science & Technology* **42**, 822–830. doi:10.1021/es0716103

Anon. (2004) Kandosols. In 'Australian Soils and Landscapes: an illustrated compendium'. pp. 296–313. (CSIRO Publishing: Melbourne)

Anon. (2007) 'Reef Water Quality Protection Plan, Action D8 Discussion Paper: Nutrient Management Zones.' pp. 17–19. (Department of Primary Industries and Fisheries: Brisbane, Qld)

Anon. (2009) 'Queensland Water Quality Guidelines Version 3.' (Department of Environment and Resource Management: Brisbane, Qld)

Boesch DF, Brinsfield RB, Magnien RE (2001) Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration and challenges for agriculture. *Journal of Environmental Quality* **30**, 303–320. doi:10.2134/jeq2001.302303x

Bremner JM, Mulvaney CS (1982) Nitrogen—total. In 'Methods of soil analysis. Part 2. Chemical and microbiological properties'. 2nd edn. pp. 711–733. (American Society of Agronomy and Soil Science Society of America: Madison, WI)

Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* **8**, 559–568. doi:10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2

Colwell JD (1965) An automated procedure for the determination of phosphorus in sodium hydrogen carbonate extracts of soils. *Chemistry & Industry* **22**(May), 893–895.

Fabricius KE (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* **50**, 125–146. doi:10.1016/j.marpolbul.2004.11.028

Fabricius K, De'ath G, McCook L, Turak E, Williams DM (2005) Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. *Marine Pollution Bulletin* **51**, 384–398. doi:10.1016/j.marpolbul.2004.10.041

Flaig EG, Reddy KR (1995) Fate of phosphorus in the Lake Okeechobee watershed, Florida, USA: overview and recommendations. *Ecological Engineering* **5**, 127–142. doi:10.1016/0925-8574(95)00021-6

Hart MR, Quin BF, Long Nguyen M (2004) Phosphorus runoff from agricultural land and direct fertilizer effects: A review. *Journal of Environmental Quality* **33**, 1954–1972. doi:10.2134/jeq2004.1954

Hodgkin EP, Hamilton BH (1993) Fertilizers and eutrophication in southwestern Australia: Setting the scene. *Fertilizer Research* **36**, 95–103. doi:10.1007/BF00747579

McColl RHS, White E, Gibson AR (1977) Phosphorus and nitrate run-off in hill pasture and forest catchments, Taita, New Zealand. *New Zealand Journal of Marine and Freshwater Research* **11**, 729–744. doi:10.1080/00288330.1977.9515709

McDowell RW, Sharpley AN (2003) Phosphorus solubility and release kinetics as a function of soil test P concentration. *Geoderma* **112**, 143–154. doi:10.1016/S0016-7061(02)00301-4

McDowell RW, Littlejohn RP, Blennerhassett JD (2010) Phosphorus fertilizer form affects phosphorus loss to waterways: a paired catchment study. *Soil Use and Management* **26**, 365–373. doi:10.1111/j.1475-2743.2010.00289.x

McKergow LA, Prosser IP, Hughes AO, Brodie J (2005) Regional scale nutrient modelling: exports to the Great Barrier Reef World Heritage Area. *Marine Pollution Bulletin* **51**, 186–199. doi:10.1016/j.marpolbul.2004.11.030

Milestone (1995) 'MLS-1200 MEGA Microwave Digestion System with MDR Technology—Operation Manual.' (Milestone: Sorisole (BG) Italy)

Mitchell C, Brodie J, White I (2005) Sediments, nutrients and pesticide residues in event flow conditions in stream of the Mackay Whitsunday Region, Australia. *Marine Pollution Bulletin* **51**, 23–36. doi:10.1016/j.marpolbul.2004.10.036

Moody PW, Bolland MDA (2001) 'Soil phosphorus levels in fruits, vines and nuts.' p. 215. In 'Soil analysis—an interpretation manual'. (Eds Peverill, Sparrow and Reuter) (CSIRO Publishing: Melbourne)

Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* **27**, 31–36. doi:10.1016/S0003-2670(00)88444-5

Ng Kee Kwong KF, Bholah A, Volcy L, Pynee K (2002) Nitrogen and phosphorus transport by surface runoff from a silty clay loam soil under sugarcane in the humid tropical environment of Mauritius. *Agriculture, Ecosystems & Environment* **91**, 147–157. doi:10.1016/S0167-8809(01)00237-7

Puustinen M, Koskiaho J, Peltonen K (2005) Influence of cultivation methods on suspended solids and phosphorus concentrations in surface runoff on clayey sloped fields in boreal climate. *Agriculture, Ecosystems & Environment* **105**, 565–579. doi:10.1016/j.agee.2004.08.005

Rayment GE, Bloesch PM (2006) Phosphorus fertility assessment of intensively farmed areas of catchments draining to the Great Barrier Reef World Heritage Area: I. Soil phosphorus status. *Communications in Soil Science and Plant Analysis* **37**, 2249–2264. doi:10.1080/00103620600817572

Rayment GE, Lyons DJ (2011) 'Soil chemical method—Australia.' (CSIRO Publishing: Melbourne)

Rohde K, Bush A (2011) Paddock to Sub-catchment Scale Water Quality Monitoring of Sugarcane Management Practices. Interim Report, 2009/10 Wet Season, Mackay Whitsunday Region. Queensland Department of Environment and Resource Management, for Reef Catchments Mackay Whitsunday Inc., Australia.

Rohde K, Bush A, Agnew J (2011) Paddock to Sub-catchment Scale Water Quality Monitoring of Sugarcane Management Practices. Interim Report, 2010/11 Wet Season, Mackay Whitsunday Region. Department of Environment and Resource Management, Queensland Government, for Reef Catchments (Mackay Whitsunday Isaac) Limited, Australia.

SILO (2005) Enhanced meteorological data [Online]. Available at: www.longpaddock.qld.gov.au/silo

Stephenson RA, Gallagher EC, Pepper PM (2002) Macadamia yield and quality responses to phosphorus. *Australian Journal of Agricultural Research* **53**, 1165–1172. doi:10.1071/AR02012

Stork PR, Jerie PH (2003) Initial studies of the growth, nitrogen sequestering and de-watering potential of perennial grass selections for use as nitrogen catch crops in orchards. *Australian Journal of Agricultural Research* **54**, 27–37. doi:10.1071/AR02080

Stork PR, Jerie PH, Callinan APL (2003) Subsurface drip irrigation of semi permanent raised vegetable beds: I. Leaching of nitrogen and phosphate under current commercial practice. *Australian Journal of Soil Research* **41**, 1283–1304. doi:10.1071/SR02145

Stork PR, Bennett FR, Bell MJ (2008) The environmental fate of diuron under a conventional production regime in a sugarcane farm during the plant cane phase. *Pest Management Science* **64**, 954–963. doi:10.1002/ps.1593

Stork PR, Lyons DJ, Bell MJ (2009) Losses of nutrient nitrogen in surface runoff from a plantation horticulture farm in coastal Queensland. *Australian Journal of Soil Research* **47**, 565–573. doi:10.1071/SR08238

Verburg K, Bridge BJ, Bristow KL, Keating BA (2001) Measured soil properties. In 'Properties of selected soils in the Gooburrum–Moore Park area of Bundaberg'. pp. 13–56. CSIRO Land & Water Technical Report 09/01, CSIRO, Canberra.